The impact of enhanced He and CNONa abundances on globular cluster relative age-dating methods

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ABSTRACT

The impact that unrecognised differences in the chemical patterns of Galactic globular clusters have on their relative age determinations is studied. The two most widely used relative age-dating methods, horizontal and vertical, together with the more recent relative MS-fitting method, were carefully analyzed on a purely theoretical basis. The BaSTI library was adopted to perform the present analysis. We find that relative ages derived using the horizontal and vertical methods are largely dependent on the initial He content and heavy element distribution. Unrecognized cluster-to-cluster chemical abundance differences can lead to an error in the derived relative ages as large as ∼0.5 (or ∼6 Gyr if an age of 12.8 Gyr is adopted for normalization), and even larger for some extreme cases. It is shown that the relative MS-fitting method is by far the age-dating technique

for which undetected cluster−to−cluster differences in the He abundance have less impact. Present results are used in order to pose constraints on the maximum possible spread in the He and CNONa elements abundances on the basis of the estimates - taken from the literature - of the Galactic globular clusters relative age dispersion obtained with the various relative age-dating techniques. Finally, it is shown that the age–metallicity relation found for young Galactic globular clusters by the GC Treasury program is a real age sequence and cannot be produced by variations in the He and/or heavy element distribution.

Subject headings: stars: evolution − Galaxy: globular clusters: general

1. Introduction

Galactic globular clusters (GGCs) are the most ancient objects known for which reliable ages can be determined, and as the Universe cannot be younger than the oldest objects it contains, GGCs provide one of the most robust constraints that we have on cosmological models. However, absolute GGCs ages have to be estimated in order to apply this constraint. Although significant improvements in the absolute GGCs age estimates have been obtained in the last decade, they are still affected by both observational and theoretical uncertainties (Vandenberg et al. 1996; Cassisi et al. 1998; Cassisi 2009) at the $\approx 20\%$ level. Nevertheless, it is possible to determine relative GGC ages with the accuracy required to address some outstanding problems, such as those related to the Milky Way's formation process. The pivotal importance of these problems and the need to improve age estimates as far as possible are the basis of the huge effort devoted in recent decades to the gathering of the relative ages of GGCs. As a consequence, there exists quite a rich literature dedicated to this fundamental topic (Stetson et al. 1996; Sarajedini et al. 1997; Rosenberg et al. 1999; Salaris & Weiss 2002; De Angeli et al. 2005; Marín-Franch et al. 2009, and references therein).

The relative age−dating techniques for GGCs - almost universally adopted - can be separated into two basic classes: those methods that are based on brightness difference measurements - the *vertical* method -, and those that are based on color difference measurements - the *horizontal* method - in the color–magnitude diagram (CMD). The most commonly adopted of the *vertical* methods is the magnitude difference between the main sequence turn-off (MSTO) and the zero age horizontal branch (ZAHB), usually estimated starting from the level of the RR Lyrae instability strip. The *horizontal* method is based on the measurement of the color difference between the MSTO and a point in the lower part of the red giant branch (RGB).

It is clear that both approaches are independent of distance, reddening, and uncertainty in the adopted photometric zero points. However, apart from this common characteristic, the two methods present different advantages and drawbacks. In particular, from the point of view of their theoretical calibration, although the dependence of the ZAHB luminosity on the metallicity is still controversial, the vertical method seems to be more reliable than the horizontal one, which is strongly affected by the non-negligible uncertainties related to the treatment of superadiabatic convection and color-T_{eff} relations. As a result, relative ages determined using the horizontal method are strongly model-dependent. On the other hand, from the observational point of view, the horizontal method seems to be largely unaffected - or in any case to quite a minor extent - by the difficulty of measuring the MSTO brightness due to its verticality in the CMD. An accurate determination of the ZAHB luminosity can also be a thorny problem, in particular for clusters at the extreme boundaries of the metallicity distribution, which generally have a red (or blue) horizontal branch and no RR Lyrae stars. In both methods, in order to minimize both observational and theoretical uncertainties in the relative age determination, the magnitude or the color difference estimated for a GGC is compared with that of a GGC of similar metallicity. A detailed discussion of the advantages and disadvantages of all the differential age-dating methods can be found in Stetson et al. (1996) and we refer the interested reader to the quoted reference.

Marín-Franch et al. (2009) have quite recently performed a detailed analysis of the relative ages of a sizeable sample of GGCs. In order to increase the level of accuracy in their age estimates they have developed an independent method for estimating the MSTO brightness difference between two GGCs of similar metallicity. This method is based on a simultaneous fit of the fainter portion of the MS - whose location is quite insensitive to cluster age but largely dependent on cluster metallicity - and the lower portion of the RGB - whose location is strongly dependent on the cluster chemical composition (hereinafter, the *relative MS-fitting*, rMSF method). A careful analysis of the advantages and uncertainties of this method has been performed by Marín-Franch et al. (2009) and will not be repeated here.

It is important to note that all relative age-dating methods are based on the implicit assumptions that all GGCs, apart from the well known differences in their iron content and, eventually, in age, are relatively similar objects, i.e., with negligible - if any - differences in the helium content and/or heavy elements distribution. However, this common idea has been severely challenged in recent decades by the growing evidence, based on accurate spectroscopical measurements, that quite peculiar chemical patterns among various GGCs with the same iron content do exist, and quite often also among stars belonging to the same cluster (for a complete review on this issue we refer the reader to Gratton et al. 2004).

Even more surprising has been the recent discovery that many GGCs host multiple stel-

lar populations (Bedin et al. 2004; Piotto et al. 2005, 2007; Milone et al. 2008; Cassisi et al. 2008), whose photometric properties can be understood in terms of sometimes quite large differences in the initial He content and/or in the heavy elements distributions and/or age. On the basis of the quoted peculiar photometric and spectroscopic properties, a possibility now considered more plausible is that the multi-population evidence is not a peculiarity of a restricted number of objects, but on the contrary, that it could be a common feature in the GGC system. The main difference is that some clusters could have the capability of retaining the different stellar populations, whereas others could at present be formed completely (D'Ercole et al. 2008; D'Antona, & Caloi 2008), or at a significant level (between 50 and 70%), by second generation stars (Carretta et al. 2009).

It is evident that the presence of observationally deceptive differences in the chemistry of GGCs might have a huge impact on relative age measurements. In fact, observational differences between two GGCs of similar metallicity, as detected with any of the quoted techniques, could be erroneously interpreted as due to an age difference when - on the contrary - it might only be due to an unrecognized difference in the chemical abundance pattern.

This issue has been recently investigated by D'Antona et al. (2009), who have only considered the specific case of the two GGCs (NGC 1851 and NGC 6121) and showed that the brightness difference existing between the sub-giant branches of these two GGCs can be explained as due to a difference in the CNO element abundance, even under the hypothesis that the two clusters are perfectly coeval.

In this article, we wish to address this issue in greater detail and more extensively, but only on purely theoretical grounds. It is worth noting that we do not investigate the robustness of the theoretical calibration of each independent age-dating method. We use a homogeneous set of stellar models in a completely differential approach for estimating how unrecognized differences in the chemical patterns of GGCs affect the relative age results obtained with the commonly adopted methods.

The plan of this paper is as follows: in the next section, the adopted theoretical framework is presented; in Section 3 we briefly review the relative age−dating techniques that we'll take into account in present work; in Section 4 we present our analysis by discussing individually each age-dating method; and we close with our conclusions and final remarks.

2.   The theoretical framework

The present analysis has been performed by using the BaSTI[1] library of stellar models and isochrones computed for the α-enhanced mixture presented by Pietrinferni et al. (2006). These models cover the whole metallicity range of GGCs, and have been computed by assuming a primordial He content equal to Y=0.245 (see Cassisi et al. 2003, and references therein) and a He enrichment ratio $\Delta Y / \Delta Z = 1.4$. From now on, these will be referred to as *reference* isochrones. For a detailed discussion of the adopted physical inputs we refer to Pietrinferni et al. (2004, 2006), while for a careful discussion of the adopted color-T_{eff} relation and bolometric scale we refer to Cassisi et al. (2004) and Bedin et al. (2005).

For the aim of testing the impact of an enhanced He content, we have computed an additional extended set of stellar models for low-mass stars for both the H- and He-burning stages, by adopting the same α-enhanced mixture but accounting for three larger He contents; namely, Y=0.30, 0.35, and 0.40.

In this context, it is worth mentioning that for a fixed global metallicity (Z), a change in the adopted He content causes a variation in the corresponding iron content, [Fe/H], according to the well-known definition of [Fe/H] as a function of Z and Y. Usually this change is very small because the He contents adopted in stellar model computations do not differ greatly from the 'canonical' value ($0.245 \leq Y \leq 0.27$). However, when dealing with extremely He rich populations, this effect might not be completely negligible. Therefore, when computing models for a fixed [Fe/H] and a given He abundance, we rescale the global metallicity Z in order to preserve the [Fe/H] value: the metallicity Z has to be reduced when the He content is increased. This choice allows us, when comparing isochrones for various He-content assumptions, to compare isochrones for the same iron content consistently.

We recognize that the adopted He enhancements with respect to the canonical value ($Y \sim 0.25$) could appear too large to be considered realistic for GGCs. However, we emphasize that, in the present analysis, we want to investigate - on a purely theoretical basis - the dependence of the relative age determinations on unrecognized peculiar chemical patterns. For this reason, we also take into account these extreme He enhancements.

Finally, for the purpose of checking the impact of a 'peculiar' heavy element distribution on relative age-dating methods, we have also adopted the set of stellar models presented in Pietrinferni et al. (2009) accounting for an extreme CNONa chemical patterns. In order to cover the whole metallicity range sampled by GGCs properly, we have extended the original

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[1]The whole library of stellar evolutionary predictions adopted in this work, as well as additional stellar model predictions can be retrieved at the following URL address: http://www.oa-teramo.inaf.it/BASTI.

set of models to lower metallicities, so the final database of stellar models adopted in the present analysis covers an iron content range from -2.89 to -0.56.

For a detailed description of the assumed heavy element distribution and more details on these stellar models and isochrones we refer the reader to the quoted reference. However, it is important to remark that the adopted heavy element distribution corresponds to a mixture in which the sum (C+N+O) is enhanced by a factor of approximately 2 with respect to the *reference* mixture. This value is consistent - although it represents an upper limit - with the results of the spectroscopic analysis performed by Carretta et al. (2005) for the extreme values of the chemical anti-correlations observed in GGCs.

It is worth noting that the stellar models for the various chemical compositions adopted in the present work are based on the most up-to-date physics currently available and, more importantly for our aim, all evolutionary predictions are fully homogeneous and self-consistent, being based exactly on the same physical framework.

Before closing this section, we wish to note that it is quite important to perform the comparison between *reference* isochrones and those corresponding to the 'peculiar' chemical patterns at fixed iron content. The main reasons for this choice are the following: *i)* when performing relative GGC age measurements the commonly adopted procedure is to divide the whole cluster sample into sub-samples on the basis of their [Fe/H] value (that is, the parameter provided by spectroscopical measurements) and then to apply the adopted relative age dating method to each selected sub-sample; *ii)* at fixed global metallicity Z, and hence [M/H], a change in the helium content (see above) and/or in the heavy element distribution (see the discussion in Pietrinferni et al. 2009) implies a change in the corresponding [Fe/H] value. Therefore, in order to obtain reliable results, we need to use the same approach that is adopted when managing real stellar systems; that means investigating the impact of changing the helium content or the heavy element distribution at fixed [Fe/H].

3. Globular cluster relative age-dating methods

In this section, the most widely used relative age-dating methods are described. Figure 1 illustrates the horizontal, vertical and rMSF techniques, applied to 8, 10, 12, and 14 Gyr *reference* isochrones with the same metallicity. *Hubble Space Telescope* ACS/WFC filters $F606W$ ($\sim V$) and $F814W$ ($\sim I$) are used here as a guideline.

3.1. Horizontal method

VandenBerg et al. (1990) were pioneers in measuring GGC relative ages by making use of the horizontal method. They essentially derived relative ages comparing the color difference between the MSTO and the location of a well defined point in the lower RGB, located 2.5 magnitudes brighter than a point in the upper main sequence (MS) that is 0.05 magnitudes redder than the MSTO. From now on this color difference will be referred to as the horizontal parameter. This method is illustrated in the left hand panel of Figure 1, where the dependence of the horizontal parameter on age is clearly shown.

Using the *reference* isochrones described in Section 2, the horizontal parameter was computed for a wide range of ages (from 6 to 15 Gyr) and iron content (from about -2.6 to -0.3). The results are plotted in the upper panel of Figure 2. It shows the resulting horizontal parameter as a function of [Fe/H]. Lines represent model horizontal parameter in steps of 1 Gyr (solid lines) and 0.5 Gyr (dotted lines). This theoretical grid will be used to derive relative ages based on the horizontal method. To do this, the curves are interpolated using a spline surface, and therefore, ages can be retrieved by a direct comparison of the target isochrone's (or GGC's) horizontal parameter with the interpolated surface.

To evaluate the impact that unrecognized differences in the chemical patterns of GGCs have on the relative age determination, one can measure the horizontal parameter for an isochrone of given age but with a different He content and/or heavy element distribution (with respect to the *reference* set). By doing so, the age corresponding to that measured horizontal parameter can be retrieved. Finally, comparing the input with the retrieved isochrone age, it is possible to evaluate the impact of *undetected* chemical abundances differences on the age determined with the horizontal method.

3.2. Vertical method

Potentially, more reliable age indicators are those related to the brightness of the MSTO, in particular the vertical method. The first surveys of GGC relative ages using the vertical method were carried out by Gratton (1987); Peterson (1987) and Sarajedini & King (1989), who used the brightness difference between the ZAHB and the MSTO (the vertical parameter from now on) to estimate the ages of sizeable samples of GGCs. This method is illustrated in the central panel of Figure 1, where the vertical parameter dependence on age is shown. Since it is well known the ZAHB brightness level for old stellar systems, such as GGCs, is independent of age, its level is the same for the four plotted *reference* isochrones.

Following the same methodology as for the horizontal method, *reference* isochrones were

used to determine the vertical parameter as a function of age and [Fe/H]. The results are plotted in the central panel of Figure 2. Lines represent the resulting vertical parameter in steps of 1 Gyr (solid lines) and 0.5 Gyr (dotted lines). Again, the curves are interpolated using a spline surface and will be used to derive relative ages based on the vertical method. Once the theoretical grid is set up, the age of a GGC - or of an isochrone with a different He content and/or heavy elements distribution - can be determined from its vertical parameter by comparing it with the *reference* isochrone grid.

3.3.   Relative MS-fitting method

The rMSF method was first used to derive relative ages for a large, homogeneous database of GGC photometry by Marín-Franch et al. (2009). The method is discussed in detail in the quoted reference and only a brief description is presented here. The CMD location of the faint MS of a GGC is independent of its age, but highly dependent on its metallicity. For this reason, MS and RGB fitting between clusters with similar metallicity is performed. The right hand panel of Figure 1 shows an example rMSF in which the 10, 12, and 14 Gyr isochrones have been shifted in both magnitude and color to fit the CMD location of the 8 Gyr one, all isochrones having the same metallicity. The fit is performed following the prescriptions of Marín-Franch et al. (2009); that is, in a least-squares fashion and taking into account two CMD regions that have little dependence on cluster age. These regions are shaded in Figure 1. It can be seen how the rMSF method provides gives the relative brightness of the considered isochrones' MSTOs.

Again, the *reference* isochrones described in Section 2 were used to compute the theoretical grid. The lower panel of Figure 2 shows the model MS turn-off in the F606W filter $M_{F606W}^{\mathrm{MSTO}}$ as a function of [Fe/H]. Lines represent MSTO magnitudes in steps of 1 Gyr (solid lines) and 0.5 Gyr (dotted lines). The curves are interpolated using a spline surface so that one can easily estimate $M_{F606W}^{\mathrm{MSTO}} = f([\mathrm{Fe/H}], \mathrm{age})$. Finally, relative ages can be estimated by using the interpolated surface.

The rMSF method was be applied to our set of isochrones, with different a He content and/or heavy element distribution, by shifting in each case the considered isochrone in both color and magnitude to fit the corresponding same metallicity *reference* one. This procedure provides the brightness of the MSTO relative to the *reference* isochrone's MSTO, which can be used to derive the relative age as previously described.

4. Results

The impact of an enhanced initial He content or an extreme CNONa mixture on the relative ages obtained by the different dating methods is illustrated in Figure 3. Horizontal, vertical, and rMSF methods applied to isochrones with the same [Fe/H], same age, but different values of Y (upper panels) and different CNONa abundances (lower panel) are shown. The upper left hand panel shows how, for the same age and same [Fe/H], the horizontal parameter increases when decreasing Y.[2] This means that the horizontal-method derived age does not coincide with the isochrone (input) one. It depends on the Y value, the derived age being older for larger values of Y. The upper central panel illustrates the effect of Y on the vertical method. The large impact that the He content has on the ZAHB level, as well as on the MSTO brightness, can be seen. This translates into a huge effect on the vertical parameter and consequently on the derived ages. It is worth mentioning that the ZAHB and MSTO magnitude shifts as a consequence of Y variation do not compensate each other. On the contrary, increasing Y translates into a fainter MSTO and a brighter ZAHB. The effect of varying the He abundance on the rMSF method is illustrated in the upper right hand panel. Increasing Y makes the MSTO fainter, as well as the MS locus. According to the figure, both effects compensate each other during the rMSF procedure, so the method turns out to be rather insensitive to He variations.

Similar arguments can be made for the CNONa variations based on the lower panels. The lower left hand panel illustrates the effect that a different CNONa abundance has on the horizontal-method derived age. In the example of the figure, the horizontal parameter increases if an extreme CNONa mixture is considered, and this translates into a retrieved age that is younger than the input one. The lower central panel shows how the vertical parameter increases in the case of an extreme CNONa mixture. This translates into older vertical-method derived ages.

We wish to note that the ZAHB brightness level is also affected by the CNONa elements enhancement, becoming slightly brighter - at least in the case of the adopted CNONa enhancement - at fixed iron content (see the discussion in Pietrinferni et al. 2009). Needless to say, that this effect is properly taken into account when investigating the effect of a change in the CNONa distribution on the vertical-method. However, for the sake of clarity this effect

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[2]We wish to note that this monotonic behavior of the horizontal parameter as a function of the He content is not present in the whole explored metallicity and/or age range. On the basis of our own computations we have verified that this occurrence is related to the different dependence of the effective temperature of the MS TO and of the RGB on the He content. We have verified that this evidence is also supported by other independent evolutionary computations such as those by Bertelli et al. (2008) (see also Catelan et al. 2009).

is not shown in Figure 3, since for the selected iron content the ZAHB brightness difference is only of ~ 0.01 mag.

Finally, the effect of varying the heavy element distribution on the rMSF method is shown in the lower right hand panel. It can be seen that the CNONa isochrones shows a relative MSTO slightly fainter (an occurrence that mimics an older age if one ignores the 'true' age and assumes the same heavy element mixture) as the reference isochrone.

4.1. Horizontal and Vertical methods

4.1.1. Helium

For a more general analysis, the age of a set of isochrones with different values of Y was determined using the horizontal and vertical methods. A wide range of ages (8, 10, 12, and 14 Gyr) and total metallicities ([Fe/H]$=-2.62$, -2.14, -1.62, -1.31, -1.01, and -0.70) was considered. The results are shown in Figure 4. The left hand panels show the horizontal-method derived relative age as a function of [Fe/H], for different Y values. An age of 12.8 Gyr has been adopted for normalization (Marín-Franch et al. 2009). It can be seen how the obtained age coincides with the isochrone (input) age for Y$\sim$0.25 (black line) as expected because these are the *reference* isochrones used to build the theoretical grids shown in Figure 2. This is not the situation if larger values of Y are considered. It is clear that even a value of Y$\sim$0.30 (significantly larger than the canonically adopted value, but not completely ruled out - at least for the sub-populations hosted by some GGCs according to the recent observational evidence of GGCs multi-populations) translates in derived horizontal-method relative ages that are from 0.08 to 0.3 older than the input ones (or 1 to 4 Gyr, if these values are transformed to absolute ages), for iron contents larger than [Fe/H]$\geq$ -1.01. This age discrepancy is clearly larger for larger values of Y. For [Fe/H]≤ -1.31, the dependence of the horizontal method results in the He content seeming to be significantly lower. VandenBerg et al. (1990) have already analyzed the dependence of the horizontal method on Y and [O/Fe] and reached similar conclusions. They noted that the horizontal method becomes quite uncertain for metallicities larger than [M/H]~ -1.2, or iron content [Fe/H]~ -1.6.

The right hand panels of Figure 4 show the vertical-method derived age as a function of [Fe/H] for different Y values. These ages have been determined for the same set of isochrones as in the previous section but, for clarity, only 8 and 10 Gyr input ages are plotted. In this case, the obtained relative ages are from 0.2 to 0.4 (or 3 to 5 Gyr in absolute values) older than the isochrone (input) ones if Y=0.30 is considered independently of the iron content. This

result worsens if larger values of Y are taken into account, reaching relative age differences of the order of more than 0.8 (or 10 Gyr) if extreme Y=0.35 or 0.40 values are considered, as can be seen in the figure.

4.1.2. Extreme CNONa mixture

A similar analysis was done to evaluate the impact of extreme CNONa mixtures. Figure 5 shows the results of this analysis. The left hand panels show the horizontal-method derived relative age as a function of [Fe/H] for the reference (canonical) and extreme CNONa mixtures. Horizontal-method relative ages obtained in the case of extreme CNONa mixtures tend to be ~ 0.1 (that is ~ 1 Gyr in absolute age) older than the input ages, with some exceptions at intermediate iron content. In any case, no clear trend with iron content is found. These results differ from the analysis of the horizontal method dependence on [O/Fe] carried out by VandenBerg et al. (1990). They argued that the horizontal method becomes quite uncertain for intermediate- and high-metallicity GGCs. In the present analysis it is shown how this method is quite sensitive to the CNONa mixture, independently of the iron content. The origin of this difference is probably due to the differences in the adopted heavy element mixtures, as well as in the physical framework (radiative opacity, equation of state, etc.).

The right hand panels shows the vertical-method derived ages for canonical and extreme CNONa isochrones. In this case, vertical-method relative ages derived for the extreme CNONa isochrones are significantly older than the input ones for [Fe/H]$\geq \sim -2$, the difference increasing with metallicity. In the high metallicity regime, retrieved relative ages are up to ~ 0.3 (or ~ 4 Gyr) older than the input value.

In summary, the horizontal- and especially vertical-method derived ages are largely dependent on the initial He value and CNONa mixture. In other words, if the relative age of a GGC is measured using these methods, undetected differences in the He content and/or CNONa abundance translates in an unreal age determination. The difference between the measured relative age and the actual one can be of the order of ~ 0.4-0.8 (which correspond to several Gyr in absolute age), especially for high metallicity clusters. It is clear that the vertical method more sensitive to variations in Y and/or CNONa chemical abundances. We note that, while for the He content a wide interval has been explored, for the case of the extreme CNONa mixture, we have investigated only the case of an enhancement factor equal to 2 in the CNO elements abundance. It is evident that, in case of larger CNO enhancement factors, the expected difference between the input age and the retrieved one would be quite larger.

4.2. Relative MS-fitting method

The rMSF-method ages were also measured for our set of isochrones, grouping them in subsets with the same iron content. In this case, a larger age interval was considered. Results are shown in Figure 6. Error bars represent the relative age uncertainty derived from the rMSF procedure (σ_{MSF}, described in Marín-Franch et al. 2009). If He enhanced isochrones are considered, it is apparent that the measured rMSF-method relative ages tend to be slightly older than the input ones, especially for high metallicity isochrones. If all values of Y and input ages are considered, the mean determined relative age is ∼0.03 (or 0.4 Gyr if expressed in absolute age) older than the input one, showing an rms dispersion around this mean of also ∼ 0.03 (or 0.4 Gyr). It is noticeable that this result is also independent of the Y value, that is, even extreme Y values translate into a ∼0.03±0.03 relative age difference between the input and rMSF-method derived ages.

In the case of the extreme CNONa mixture, the results are shown in Figure 7. In this case, it appears that rMSF-method derived relative ages are ∼0.10±0.02 (or ∼1±0.3 Gyr in terms of absolute age) older than the actual ages. No significant trend with [Fe/H] is found.

5. Discussion

In order to present the results in a clearer and more concise way, the partial derivatives of the relative age with Y and CNONa, with different iron contents, have been calculated. The partial derivatives $\delta Age_{NORM}/\delta Y$ have been computed using the mass change in He, that is Y=0.25, 0.30, 0.35 and 0.40. For this purpose, and for each value of input age and iron content, a least squares fit has been performed to derive the slope of the Age_{NORM} as a function of Y. Finally, results for different input ages have been averaged to derive the final $\delta Age_{NORM}/\delta Y$ as a function of $[Fe/H]$. Concerning the CNONa, a similar procedure has been followed, but in this case, since the CNONa extreme mixture has a sum (C+N+O+Na) that is a factor of 2 (about 0.3 dex) larger than in the reference case, $\delta Age_{NORM}/\delta CNONa$ has been computed by accounting for a $\delta CNONa = 0.3$.

The results are shown in Figure 8, where the partial derivatives of the relative age with Y (left panel) and with CNONa (right panel) are plotted for the horizontal (red squares), vertical (blue circles) and rMSF (black triangles) methods. The left panel clearly shows that the vertical method is strongly dependent on Y for all metallicities, while the horizontal method is very sensitive to Y only for metallicities higher that [Fe/H]> −1.3. The rMSF method, on the other hand, is quite insensitive to Y for the whole metallicity interval except, maybe, for very high iron content. The right panel shows that the three methods are not

very sensitive to CNONa, rMSF method having the relative advantage of showing a CNONa dependence that is metallicity independent.

In conclusion, it is evident that both the horizontal and the vertical methods are significantly affected by undetected differences in both the initial He content and/or heavy element distribution between the stellar systems under scrutiny. Between the two methods, the worst one in this context is clearly the vertical method. With regard to the rMSF relative age technique, this is almost unaffected by any variation in the helium content, and affected by a change in the metal distribution (in particular in the CNO element abundance) as the same level of the horizontal and vertical method. On the basis of present analysis, and taking into account the advantages discussed by Marín-Franch et al. (2009), we consider the rMSF method much more suitable than other techniques for retrieving relative GGCs ages.

5.1. Delimiting the He dispersion in GGCs

It has been shown that the horizontal and particularly the vertical methods provide ages that are very sensitive to differences in chemical abundances. That is, if the relative age of a GGC is measured using these methods, undetected differences in the He content and/or CNONa abundance translates into a wrong relative age determination. The difference between the measured relative and actual ages can be of the order of ~ 0.4-0.8 (which correspond to several Gyr in absolute age), especially for high-metallicity clusters. It is clear that the vertical method is most sensitive to variations in Y and/or CNONa chemical abundances. This implies that these two relative age-dating methods are not optimum in the case of having GGCs showing different chemical patterns, as has been found observationally. Peculiar chemical patterns have been detected among various GGCs with the same iron content based on accurate spectroscopic measurements (see Gratton et al. 2004, for a thorough review). However, this drawback can be used to limit the possible cluster-to-cluster differences in He according to their measured relative ages, and in particular on the basis of the relative age dispersion.

A recent relative age study based on the vertical method has been carried out by De Angeli et al. (2005), who found a relative age dispersion of ~ 0.05, ~ 0.08 and ~ 0.03 (rms) for the low-, intermediate- ($-1.7 < $ [Fe/H] $ < -0.8$) and high-metallicity groups of GGCs, respectively. These dispersions could be due to a real age dispersion, to cluster-to-cluster He differences, or a combination of both. In any case, these values can be used to limit the He dispersion in GGCs to ~ 0.010, ~ 0.012 and ~ 0.004, according to Figure 4.

5.2. Can the He and/or CNONa spread account for the observed rMSF-derived relative ages?

Marín-Franch et al. (2009) performed a relative age study over 64 GGCs based on the rMSF method. They found that the GGC sample can be divided into two groups: (i) a population of old, coeval GGCs with an intrinsic relative age dispersion of 0.03 and no age–metallicity relation, and (ii), a group of younger GGCs with a well defined age–metallicity relation and an intrinsic relative age dispersion with respect to this relation of also 0.03. In this section, the possibility of these age dispersions and age–metallicity relation being caused by cluster-to-cluster He and/or CNONa variations is analysed.

Regarding the He, the main finding of the present paper is that the rMSF method is the relative age-dating technique for which undetected differences in the He content has less impact. The impact is small but not negligible. It has been shown that undetected differences in the He content translate into a relative age determination that is on average, and considering also extreme Y values, $\sim 0.03 \pm 0.03$ older than the actual one. But in the previous section, the possibility of having a significant He dispersion in GGCs has been ruled out: based on vertical-method relative ages results, the cluster-to-cluster He dispersion has been limited to ~ 0.01. This translates into a source of uncertainty at the level of ~ 0.004 in the derived rMSF-method relative ages, which is not significant. That is, neither the young group of GGCs' age–metallicity relation nor the 0.03 intrinsic relative age dispersion obtained by Marín-Franch et al. (2009) is produced by a He dispersion in GGCs.

As far as it concerns the existence of a real spread in the CNONa elements in the GGC system, the empirical findings, available so far, seem to show that a CNONa enhancement of a factor of 2 (the same adopted in present analysis) with respect the standard α-enhanced mixture cannot be ruled out (Carretta et al. 2005). However, this evidence is based on few GGCs, and in any case the quoted CNONa enhancement appears - so far - an upper limit (Carretta 2009, private communication).

Bearing in mind this empirical evidence, we can try to use present results in order to put further constraints on the existence of a possible spread in the CNONa element enhancement. As discussed in the previous section (see Figure 7), in the case of an enhancement of a factor of 2 (i.e., 0.3 dex), the rMSF-method derived relative ages are $\sim 0.10 \pm 0.02$ older than the actual ones. This value appear larger than the 0.03 relative age intrinsic dispersion found by Marín-Franch et al. (2009): this means that if the retrieved age dispersion is only due to a CNONa spread we can limit the 'maximum' CNONa enhancement to a factor ~ 1.2 (i.e., ~ 0.18 dex or $\sim 20\%$). Interestingly enough, this estimate is in very good agreement with currently available spectroscopic measurements for GGCs. In other words, the relative age dispersion found by Marín-Franch et al. (2009) could be entirely produced by a cluster-to-

cluster CNONa dispersion of 20% or 0.18 dex.

Finally, as a CNONa enhancement of a factor of 2 translates into a relative age change of $\sim$0.1, it cannot be the cause of the young group's age–metallicity relation (in which relative ages go from $\sim$1 to $\sim$0.5). As a conclusion, we reassert that the age–metallicity relation found in Marín-Franch et al. (2009) is a real age sequence.

6. Conclusions

In the present work, we have studied the impact that unrecognized differences in the chemical patterns of GGCs have on their relative age determinations. The two most widely used relative age-dating methods, horizontal and vertical, together with the more recent relative MS-fitting method described in Marín-Franch et al. (2009), were carefully analyzed on a purely theoretical basis. The BaSTI library of stellar models was adopted to perform the present analysis, supplemented by additional evolutionary computations for more extreme assumptions about the initial He content. Our main conclusions are summarized here:

- We find that relative ages derived using the horizontal-method are largely dependent on the initial Y value and CNONa mixture. Undetected differences in the He content and/or CNONa abundance translates in an unreal age determination. The difference between the measured relative age and the actual one is in the range from 0.08 to 0.3 (or 1 to 4 Gyr, if these values are transformed to absolute ages), this result worsens for high metallicity clusters.

- For the vertical method, we find that the obtained relative ages are from 0.2 to 0.4 (or from 3 to 5 Gyr in absolute values) older than the isochrone (input) ones if a helium enhancement of Y=0.3 is considered, independently of the metallicity. This result worsens if larger - more extreme - values of Y are taken into account, reaching age differences of the order of more than 0.8 ($\sim$ 10 Gyr) if extreme Y=0.35 or 0.4 values are considered. The vertical method is most sensitive to cluster-to-cluster undetected variations in Y.

- We find that the vertical-method can be used to limit the possible cluster-to-cluster differences in He according to their measured relative ages. In particular, the Y dispersion in GGCs has been limited to $\sim$0.01.

- We find that the rMSF method is the relative age-dating technique for which undetected differences in the He content has less impact. It has been shown that neither the

young group of GGCs' age–metallicity relation nor the 0.03 intrinsic relative age dispersion found by Marín-Franch et al. (2009) is produced by a He dispersion in GGCs.

- When considering the possibility of undetected differences in the CNONa mixture, our results allow us to constrain the maximum possible enhancement of CNONa elements, which should be of the order of 1.2; i.e., ~ 0.18 dex, with respect a 'standard' $\alpha-$enhanced mixture.

- The relative age dispersion found by Marín-Franch et al. (2009) could be entirely produced by a cluster-to-cluster CNONa dispersion.

- We reassert that the age–metallicity relation found in Marín-Franch et al. (2009) is a real age sequence.

- When taking also into account the advantages of the rMSF technique with respect to the other relative age dating methods, it appears that, so far, that the rMSF method is the approach that is much to be preferred for retrieving GGC chronology.

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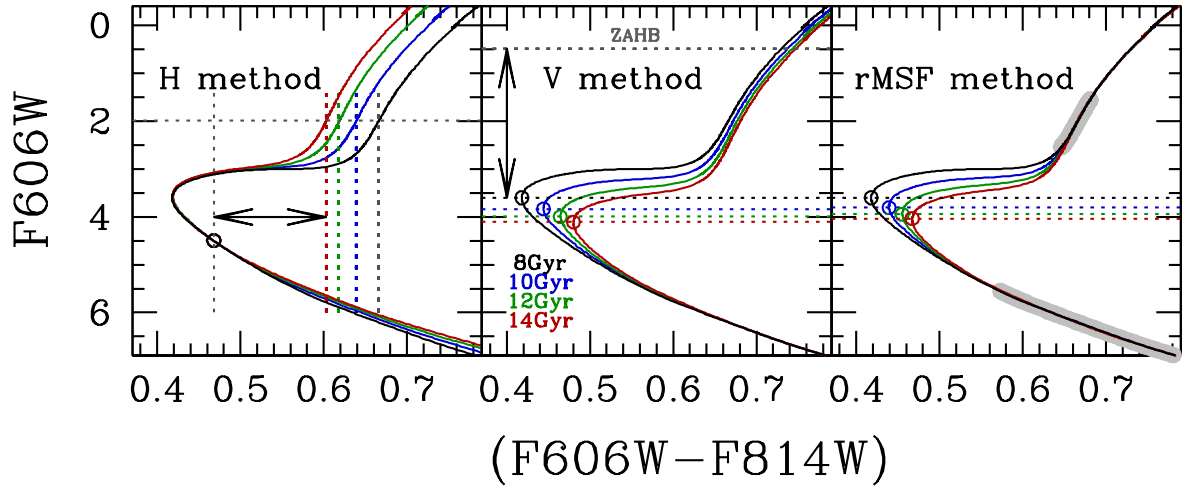
Fig. 1.— he relative dating methods. The BaSTI α-enhanced isochrones with [Fe/H]=-1.31, Y=0.248 and ages 8, 10, 12 and 14 Gyr are shown.
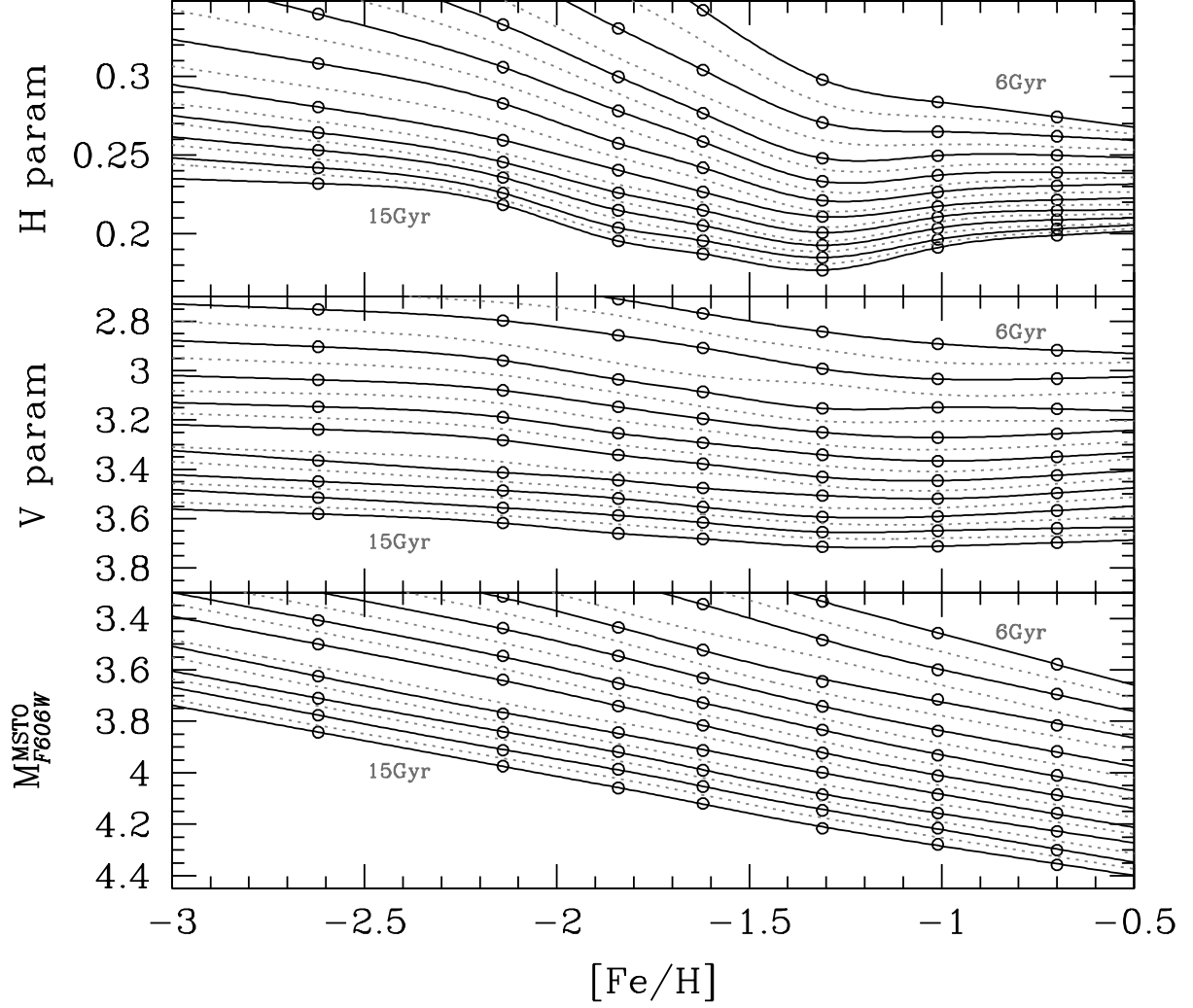
Fig. 2.— Theoretical grids for the H and V parameters, together with the $M_{F606W}^{\mathrm{MSTO}}$. Open circles represent some of the isochrone measurements used for the grid computation. The adopted isochones correspond to the *reference* theoretical grid (see text for more details).
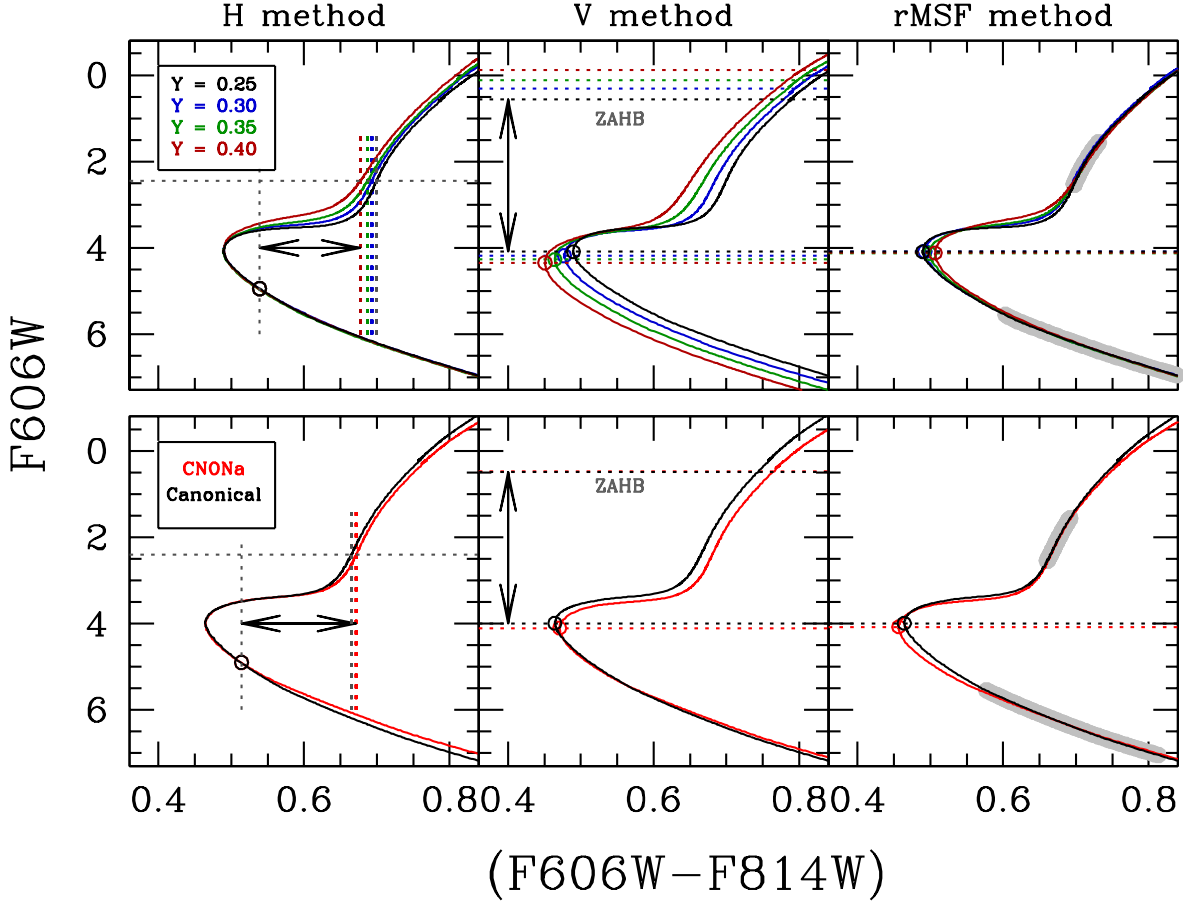
Fig. 3.— Qualitative effect of He (upper panels) and CNONa heavy element (lower panels) abundances on the derived ages for the different methods. These are BaSTI α-enhanced isochrones with [Fe/H]=−1.01 (upper panels) and ~ -1.3 (lower panels) for an age of 12 Gyr. Different Y values (0.25, 0.30, 0.35 and 0.40) and CNONa mixtures (canonical and extreme) are considered. The set of colors adopted to mark the different helium and CNONa abundances have been labeled in the figure (boxes), and is the same set of colors adopted in the following figures.
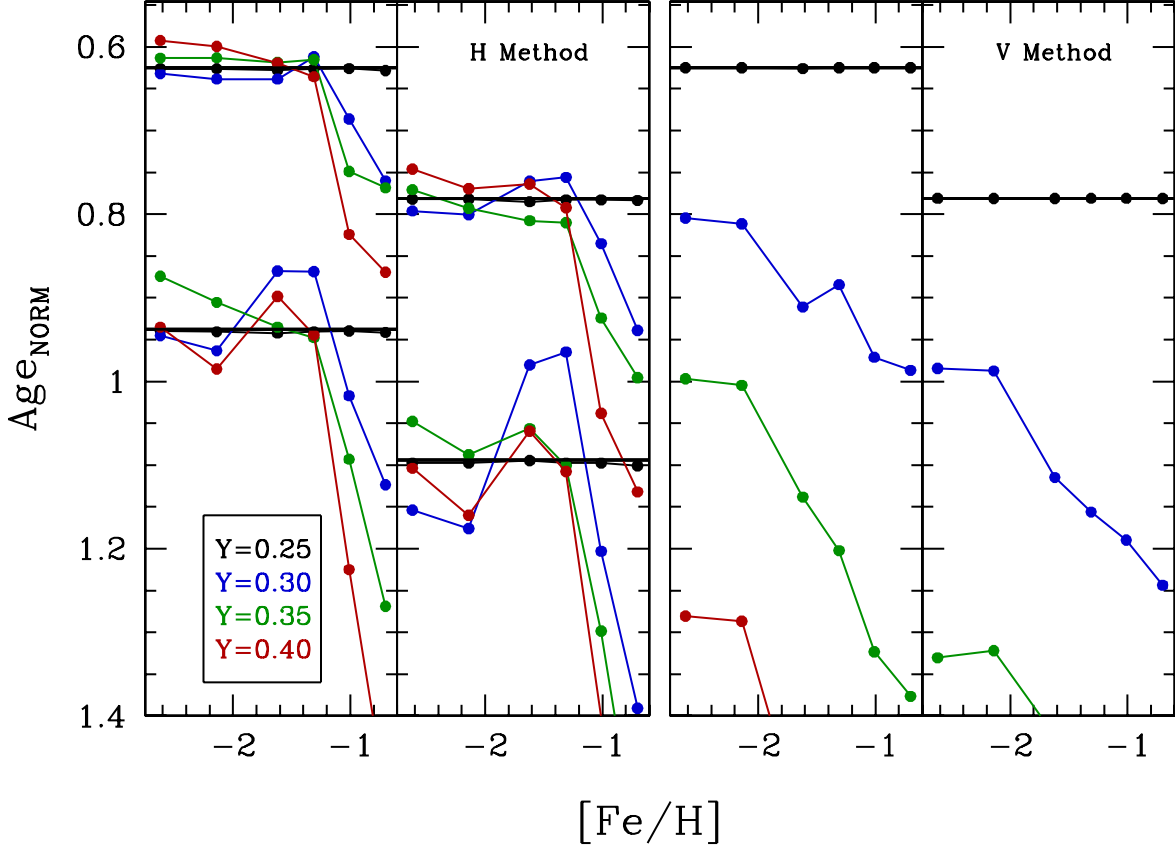
Fig. 4.— Retrieved relative ages measured using the horizontal (left hand panels) and the vertical (right hand panels) methods, as a function of [Fe/H]. Different Y values (0.25, 0.30, 0.35 and 0.40) and different input relative ages (0.62, 0.78, 0.94 and 1.09 for the horizontal method and 0.62 and 0.78 for the vertical one) are considered. The horizontal and vertical parameters measured on He-enhanced isochrones are compared with the theoretical grids for the *reference* isochrones shown in Figure 3 to derive the age.
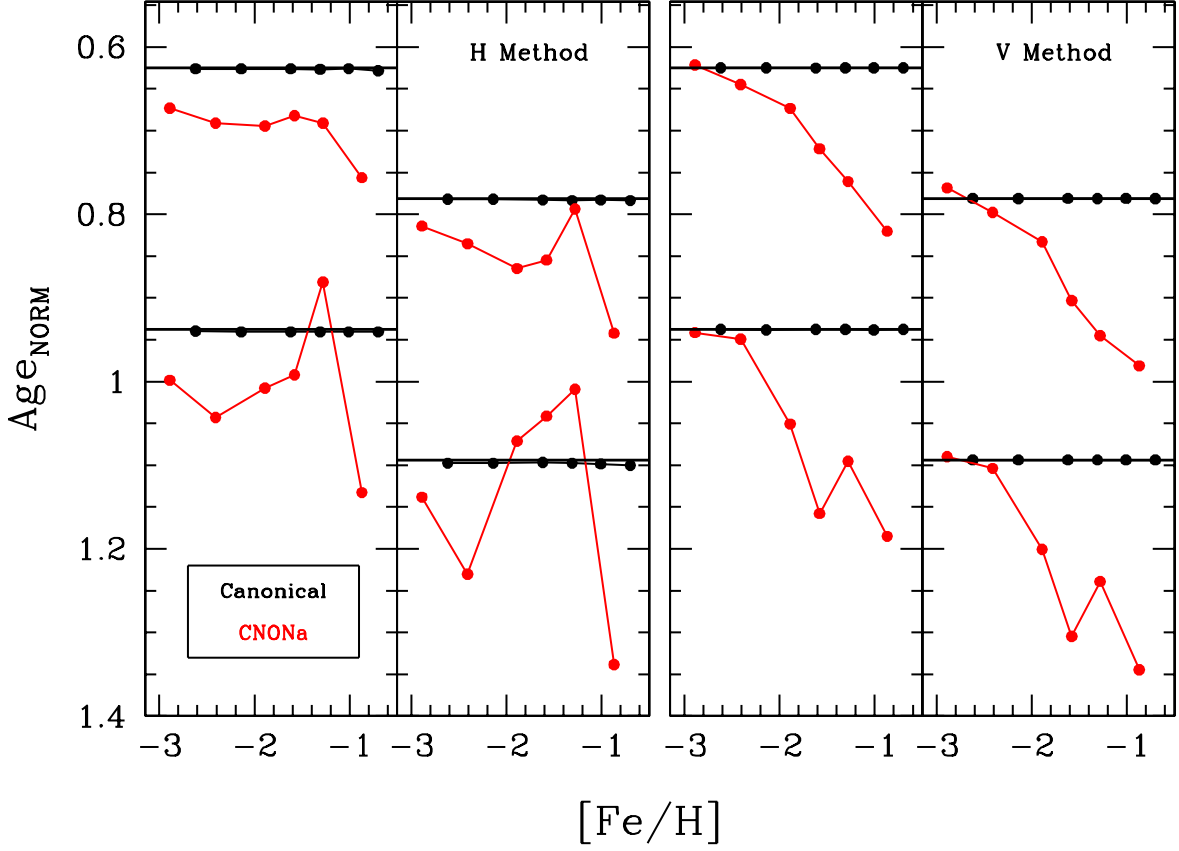
Fig. 5.— Retrieved relative ages as a function of [Fe/H], measured using the horizontal and the vertical methods. Two different CNONa mixtures and different input relative ages (0.62, 0.78, 0.94 and 1.09) have been used. The horizontal and vertical parameters measured on extreme CNONa isochrones, are compared with the theoretical grids for the *reference* isochrones shown in Figure 3 to derive the age.
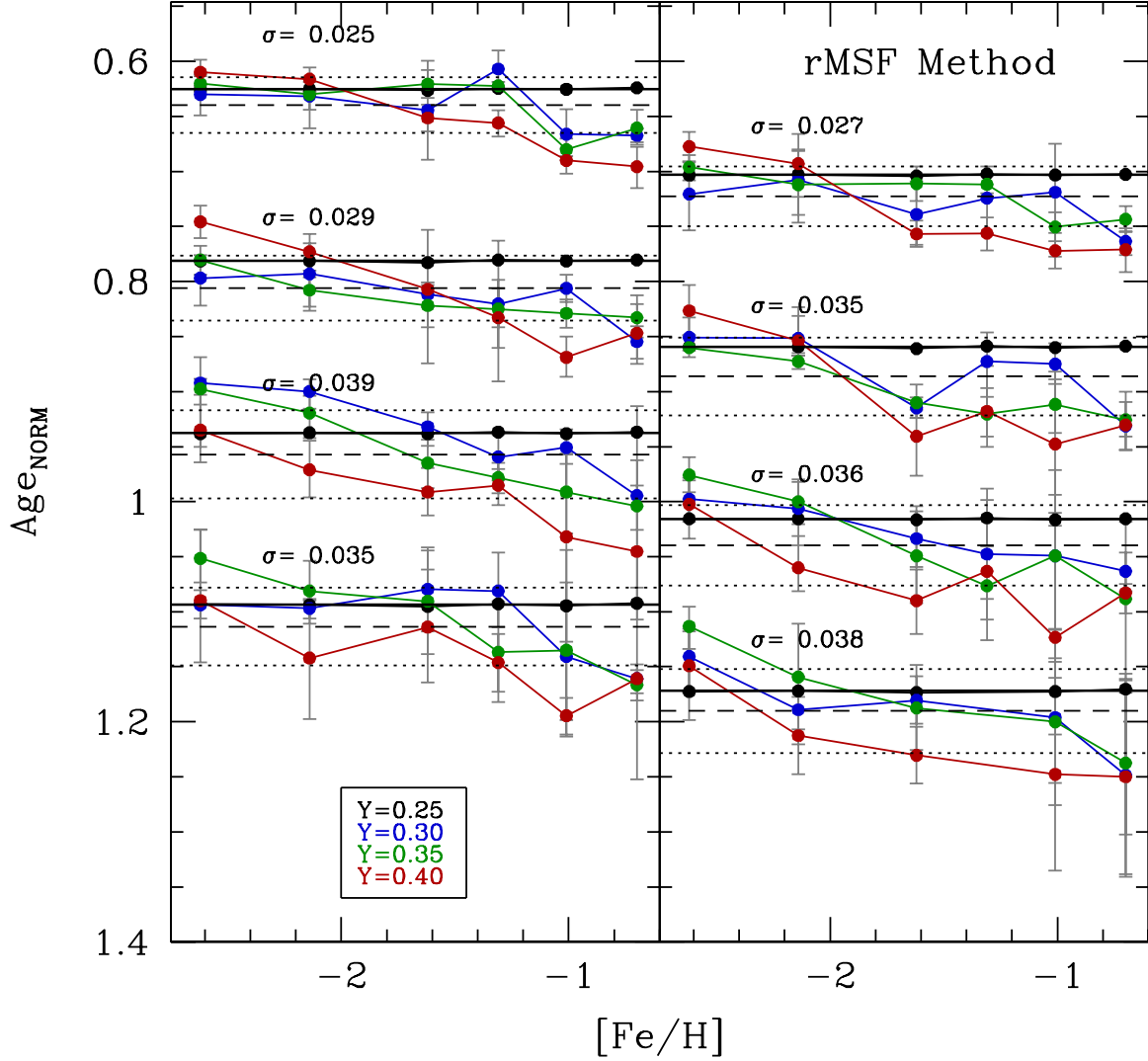
Fig. 6.— Retrieved relative ages as a function of [Fe/H], obtained by using the rMSF method. Error bars represent the relative age uncertainty derived from the rMSF procedure. Different He values (0.25, 0.30, 0.35 and 0.40) and various input relative ages (0.62, 0.70, 0.78, 0.86, 0.94, 1.02, 1.09 and 1.17) are considered. Measured parameters are compared with theoretical grid in Figure 3 to derive the age. Dashed lines show the mean measured age and dotted lines show the 1-σ interval. The value of σ is listed for all input ages.
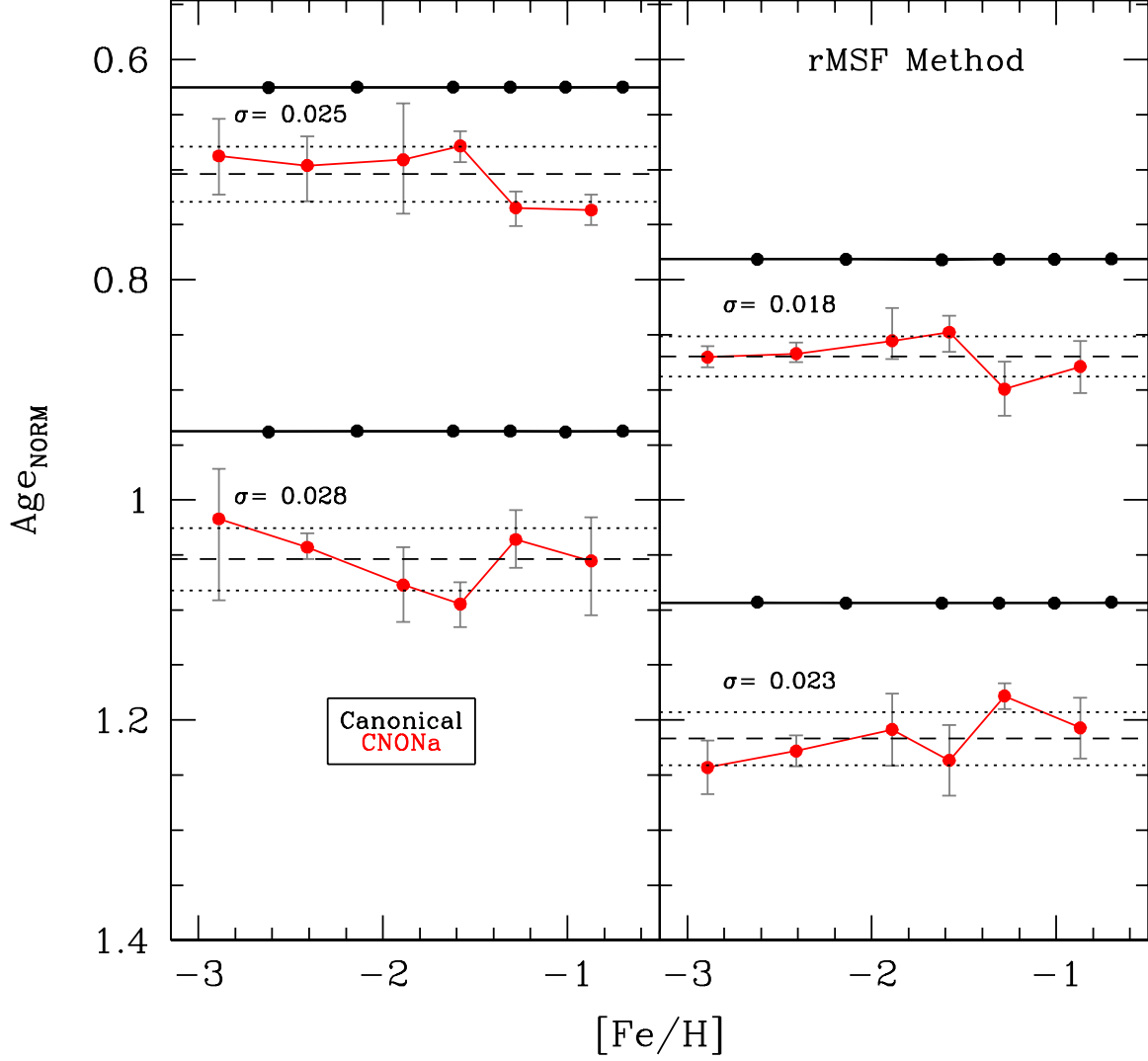
Fig. 7.— Retrieved relative ages as a function of [Fe/H] based on the rMSF method. Two different CNONa mixtures and different input ages (0.62, 0.78, 0.94 and 1.09) have been used. Dashed lines show the mean measured age for the extreme CNONa mixture isochrones, and dotted lines show the 1-σ interval. The value of σ is listed for all input ages.
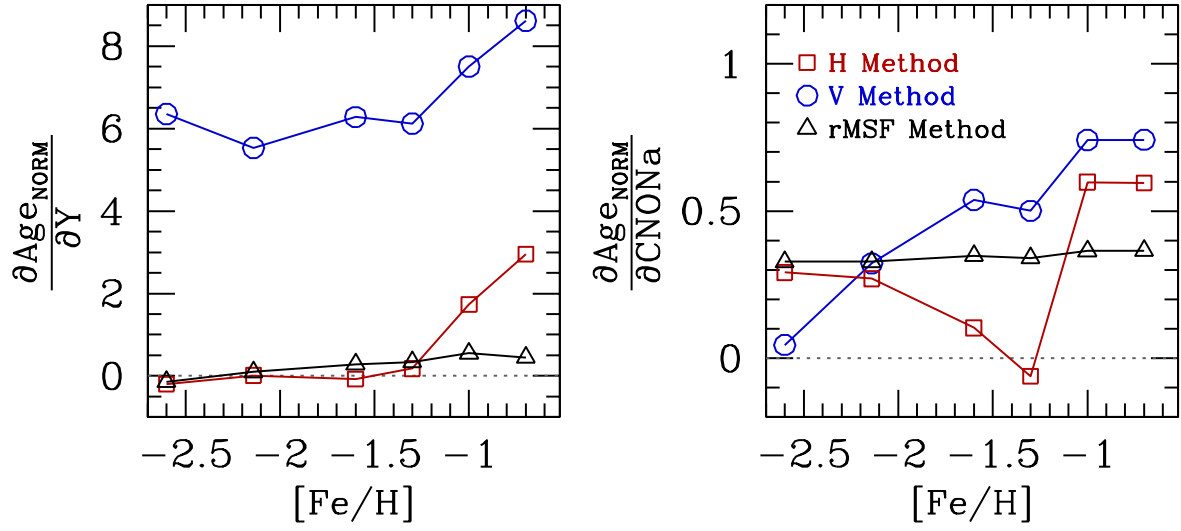
Fig. 8.— Partial derivatives of the relative age with Y (left panel) and with CNONa (right panel) calculated for the horizontal (red), vertical (blue) and rMSF (black) methods.